The supernova/gamma-ray burst/jet connection

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The observed association between supernovae and gamma-ray bursts represents a cornerstone in our understanding of the nature of gamma-ray bursts. The collapsar model (MacFadyen & Woosley 1999) provides a theoretical framework for this connection. A key element is the launch of a bi-polar jet (seen as a gamma-ray burst). The resulting hot cocoon disrupts the star while the ^{56}Ni produced gives rise to radioactive heating of the ejecta, seen as a supernova. In this discussion paper I summarise the observational status of the supernova/gamma-ray burst connection in the context of the 'engine' picture of jet-driven supernovae and highlight SN 2012bz/GRB 120422A – with its luminous supernova but intermediate high-energy luminosity – as a possible transition object between low-luminosity and jet gamma-ray bursts. The jet channel for supernova explosions may provide new insight into supernova explosions in general.

Key words: supernovae; gamma-ray bursts; jets.

1. Introduction

SN 1998bw (Galama et al. 1998; Kulkarni et al. 1998), coincident in space and time with GRB 980425, remains the prototype radio-bright, broad-lined (BL) Type Ic supernova, against which other supernova/gamma-ray bursts are measured up. GRB 980425, however, was peculiar, with an isotropic equivalent energy release in γ-rays of only $E_{\gamma,\mathrm{iso}} \sim 10^{48}$ erg. The optical lightcurve of SN 1998bw, depicted in Fig. 1, exhibited a characteristic rise to peak of about $M_V = -19.2$ mag in about 16 days, similar to a Ia supernova. MacFadyen & Woosley (1999) predicted that "*all gamma-ray bursts produced by the collapsar model will also make supernovae like SN 1998bw*". In this model, the progenitor star is a Wolf–Rayet star (Crowther 2007; Langer 2012), i.e., a massive star which has shed its envelope of hydrogen and helium, possibly through eruptions (Smith & Owocki 2006).

The ultimate proof of a SN 1998bw-like supernova associated with a 'normal' cosmological gamma-ray burst with $E_{\gamma,\mathrm{iso}} \sim 10^{52}$ erg came with the spectroscopic identification of SN 2003dh associated with GRB 030329, as a supernova spatially and temporally coincident with the gamma-ray burst, and with lightcurve properties and spectroscopic broad-line evolution very similar to that of SN 1998bw (Stanek et al. 2003; Hjorth et al. 2003).

The night before the Royal Society Discussion Meeting on "New windows on transients across the universe", GRB 120422A was observed by *Swift* and subsequently by ground-based telescopes at a redshift of 0.28. An accompanying

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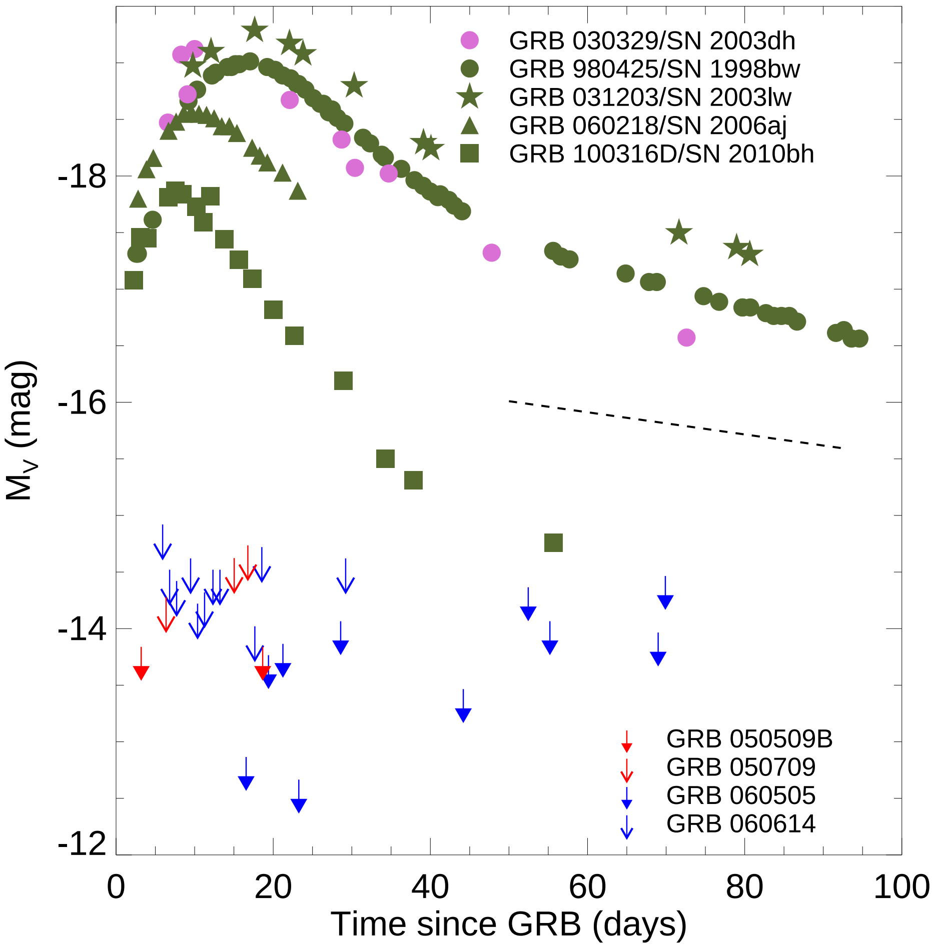

Figure 1. Optical lightcurves for the grade A (Hjorth & Bloom 2011) spectroscopic supernovae associated with gamma-ray bursts (excluding SN 2012bz). The olive points are supernovae from low-luminosity gamma-ray bursts while the orchid data points are for SN 2003dh, associated with the jet gamma-ray burst GRB 030329. There is considerable diversity in the light curves, regarding time to peak and peak magnitude. The ^{56}Co decay slope is shown for reference (dashed line). Also shown are upper limits on supernova emission from long gamma-ray bursts (blue) and short gamma-ray bursts (red) (adapted from Hjorth & Bloom 2011). A recent compilation of lightcurves of other supernovae associated with gamma-ray bursts is available in Cano et al. (2011).

supernova was predicted at the meeting and indeed reported soon after as SN 2012bz (Wiersema et al. 2012; Malesani et al. 2012).

In this paper I focus on 'jet-driven' supernovae and their relation (or lack thereof) to the different classes of gamma-ray bursts and highlight the importance of SN 2012bz/GRB 120422A. More comprehensive (and less speculative) reviews of the supernova/gamma-ray burst connection can be found in Woosley & Bloom (2006) and Hjorth & Bloom (2011).

2. Supernovae associated with long-duration gamma-ray bursts

There seem to be two types of long-duration gamma-ray bursts. The exact division is unclear but we will discuss them in turn below.

(*a*) *Low-luminosity gamma-ray bursts*

Low-luminosity gamma-ray bursts (also termed 'sub-energetic' or 'nearby' bursts) seem to be about 100 times as common as the other class discussed below (Pian et al. 2006), but because of their low luminosities they are primarily found at low redshifts as rare events (one every ~ 3 years). They typically have single-peak high-energy prompt lightcurves, soft high-energy spectra, and are often found to be X-ray flashes, i.e., gamma-ray bursts with peak energies below ~ 50 keV. Observational evidence suggests that the radio and high-energy emission is due to the breakout of a relativistic shock from the surrounding massive wind of the progenitor star (Colgate 1968; Kulkarni et al. 1998; Campana et al. 2006; Soderberg et al. 2006; Nakar & Sari 2012). Apart from SN 2003dh (and possibly SN 2012bz), the best studied supernovae related to gamma-ray bursts are all members of this class. Their lightcurves are shown in Fig. 1.

(*b*) *Jet gamma-ray bursts*

These are also known as 'normal' or 'cosmological' gamma-ray bursts (or 'collapsar' bursts, although this is a somewhat theory-laden term) and are characterised by more complex prompt emission lightcurves and higher energies, luminosities and peak energies. They are believed to arise from emission from a relativistic jet at large distances from the progenitor star.

Observing a supernova related to a gamma-ray burst at higher redshift is challenging because of possible contamination by the host galaxy (which often appears unresolved in ground-based observations) and the afterglow. This is illustrated in Fig. 2. Indeed, as shown by Lipkin et al. (2004), the lightcurve of GRB 0303029 did not exhibit a conspicuous lightcurve bump from SN 2003dh because it was afterglow dominated. Besides 2003dh (shown in Fig. 1), the best example of a supernova related to a gamma-ray burst in this class is SN 2010ma (Sparre et al. 2011) (and possibly SN 2012bz).

(*c*) *Statistical properties of supernovae associated with gamma-ray bursts*

Inferring statistical properties of supernovae associated with gamma-ray bursts requires a well-defined sample. For this purpose Hjorth & Bloom (2011) devised a grading scheme for each supernova claimed in the literature to be related to

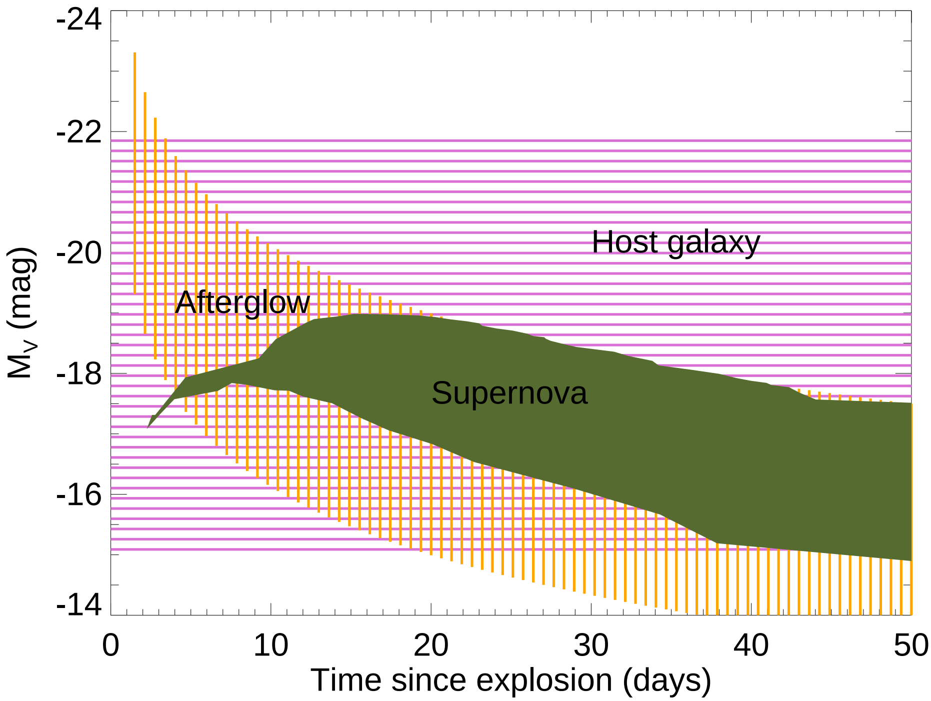

Figure 2. Schematic diagram illustrating the challenges in detecting supernova light on the background of the gamma-ray burst afterglow and the host galaxy. The supernova region (olive) reflects the range in lightcurves shown in Fig. 1. The afterglow is assumed to decay as $t^{-1.5}$; the afterglow region reflects the range in afterglow brightness reported by Kann et al. (2010). The range in host galaxy magnitudes reflect those detected in the TOUGH survey (Hjorth et al. 2012). The diagram shows that observed lightcurves may either be supernova, afterglow or host galaxy dominated. All situations are encountered in nature.

a gamma-ray burst. The evidence for a supernova was graded A–E.[1] Based on supernovae with grades A,B,C we plot in Fig. 3 the distribution of peak supernova magnitudes as a function of isotropic equivalent luminosity in γ-rays. Defining $L_{\gamma,\mathrm{iso}} = E_{\gamma,\mathrm{iso}} T_{90}^{-1}(1+z)$ we have tentatively identified low-luminosity gamma-ray bursts as having $L_{\gamma,\mathrm{iso}} < 10^{48.5}$ erg s^{-1} and jet gamma-ray bursts as having $L_{\gamma,\mathrm{iso}} > 10^{49.5}$ erg s^{-1}. There is a real dispersion in the peak magnitudes; supernovae related to gamma-ray bursts are evidently not standard candles. It remains an open question whether they are standardizable similar to Type Ia supernovae (Stanek et al. 2005; Cano et al. 2011). It is evident that the lightcurves of the subsample of supernovae shown in Fig. 1 exhibit a clear correlation between the peak magnitude and the width of the peak.

We note that beaming and viewing angle can significantly affect the inferred high-energy luminosity (Granot & Ramirez-Ruiz 2010). For example, GRB 091127, which appears in the high-luminosity (jet) part of Fig. 3, has been suggested to be a sub-energetic burst (Troja et al. 2012) due to a beaming correction. Nevertheless, it is evident that there appears to be a parabola-shaped upper envelope to the brightness of supernovae as a function of high-energy luminosity. By the time of the meeting there were no gamma-ray bursts with convincing supernovae in the range $10^{48.5}$ erg $< E_{\gamma,\mathrm{iso}} < 10^{49.5}$ erg. This changed with SN 2012bz/GRB 120422A which fills this gap in high-energy luminosity as one of the brightest supernovae associated with a gamma-ray burst ever detected (Melandri et al. 2012).

How do these peak magnitudes compare to other similar supernovae, i.e., Type Ic supernovae, with no hydrogen or helium in their spectra? Using the well-defined sample of normal Ic supernovae from Drout et al. (2011) and a more heterogeneous sample of broad-lined Ic supernovae from a variety of sources, we plot in Fig. 4 cumulative histograms of their peak magnitudes. Type Ic supernovae seem to be fainter than supernovae related to gamma-ray bursts while the situation is less clear-cut for Ic-BL supernovae with no GRBs. We note that strong observational evidence (grade A–C) quite naturally will bias our sample against fainter supernovae.

The comparison to Ic-BL is interesting because the rates of low-luminosity gamma-ray bursts and Ic-BL are comparable, suggesting perhaps a common origin and indicates that low-luminosity gamma-ray bursts, as expected, may not be strongly beamed (Podsiadlowski et al. 2004).

3. Supernova-less gamma-ray bursts

Two classes of gamma-ray bursts are not accompanied by bright supernovae.

(*a*) *Short gamma-ray bursts*

Short-duration, hard-spectrum gamma-ray bursts (Kouveliotou et al. 1993), with durations $T_{90} < 2$ s, are known not to lead to supernovae. In Fig. 1 we

[1] We have created a website (http://www.dark-cosmology.dk/GRBSN) dedicated to providing updates to the list of supernovae related to gamma-ray bursts, the grading of the observational evidence for a supernova, and supplementary information on the supernovae and the associated gamma-ray bursts.

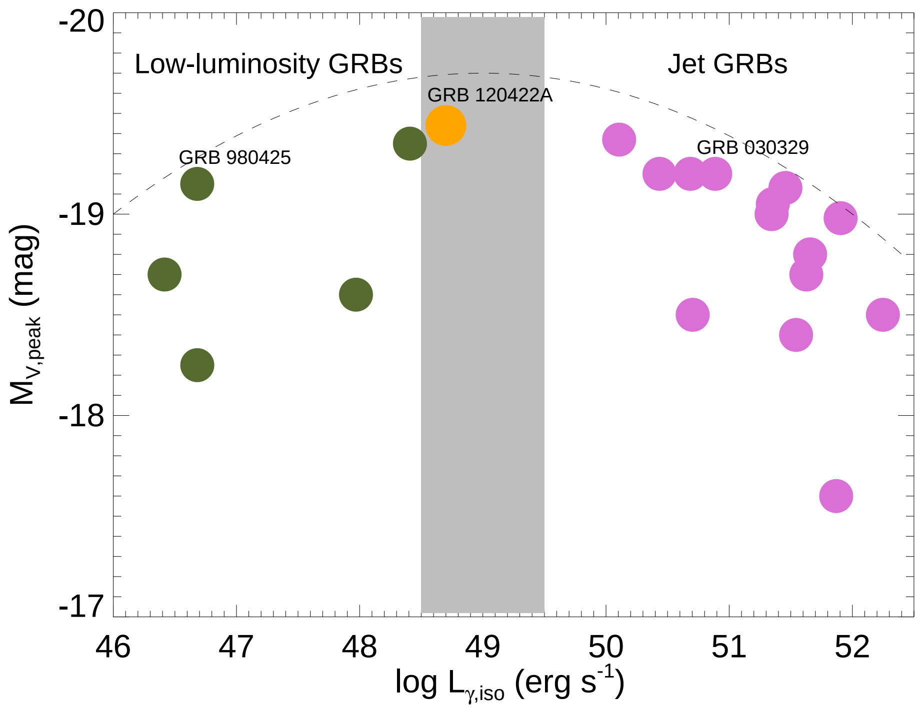

Figure 3. Supernova optical peak brightness versus gamma-ray burst isotropic luminosity (Amati et al. 2008, 2009) for grade A,B,C systems (Hjorth & Bloom 2011). Low-luminosity gamma-ray burst supernovae ($E_{\gamma,\mathrm{iso}} < 10^{48.5}$ erg, olive) and supernovae from jet gamma-ray bursts ($E_{\gamma,\mathrm{iso}} > 10^{49.5}$ erg, orchid) have similar distributions of peak brightness. SN 2012bz/GRB 120422A is highlighted (orange) as a possible transition object in the grey area $10^{48.5}$ erg $< E_{\gamma,\mathrm{iso}} < 10^{49.5}$ erg (Zhang et al. 2012).

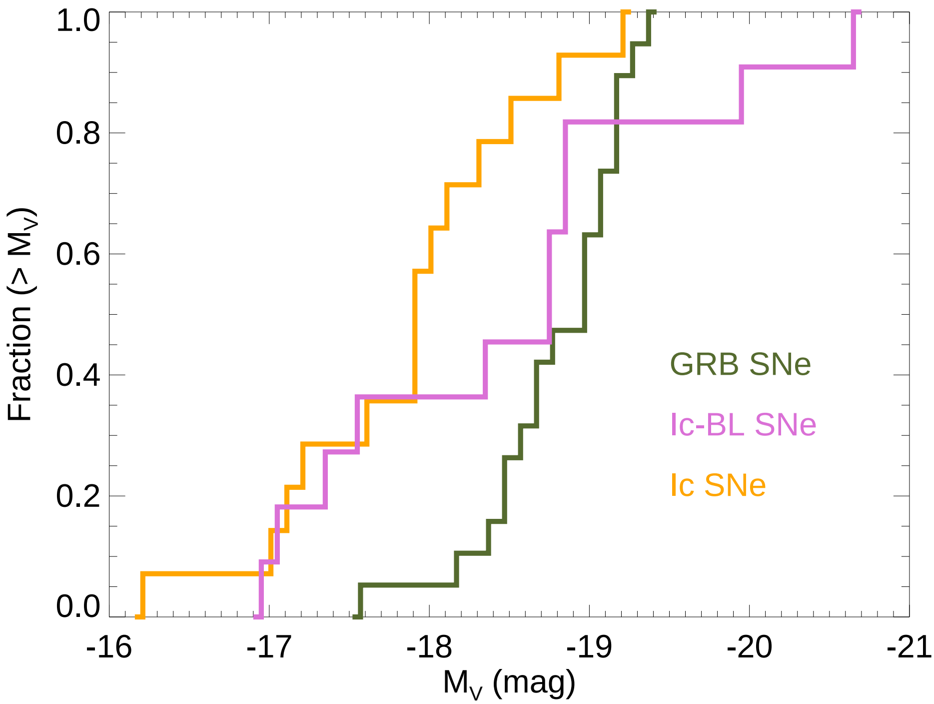

Figure 4. Cumulative distributions of the brightness of different kinds of Ic supernovae. The supernovae associated with gamma-ray bursts graded A, B, or C are from Hjorth & Bloom (2011). The normal Ic supernovae are from Drout et al. (2011). The Ic-BL distribution comes from a variety of sources and as such represents a more ill-defined sample. The gamma-ray burst supernovae generally appear brighter than normal Ic supernovae, although it should be noted that they are likely biased against faint systems. The brightness distribution of Ic-BL is probably consistent with that of gamma-ray burst supernovae although there may be a lack of very bright gamma-ray burst supernovae.

have plotted the upper limits on the existence of supernovae accompanying GRBs 050509B (Hjorth et al. 2005a) and 050709 (Hjorth et al. 2005b). These constrain any supernova to be about 100 times fainter than SN 1998bw at peak. This is consistent with short gamma-ray bursts being the results of compact object mergers.

The data also rule out the existence of an early rebrightning in GRB 050509B (Hjorth et al. 2005a) at 1.5 days in the restframe. Bright transient emission, dubbed a 'mini SN' (Li & Paczyński 1998; Rosswog & Ramirez-Ruiz 2002), 'kilonova' (Metzger et al. 2010) or 'macronova' (Kulkarni 2005), is expected to peak around the optical-UV range within a day or so with a semi-thermal spectrum (Li & Paczyński 1998). GRB 050509B sets very strong contraints on such emission (Hjorth et al. 2005a; Kocevski et al. 2010; Roberts et al. 2011).

(*b*) *Long supernova-less gamma-ray bursts*

Perhaps surprisingly, some long-duration gamma-ray bursts are not accompanied by bright supernovae. As shown in Fig. 1, the constraints on GRBs 060505 and 060614 are about as constraining as the those related to the short gamma-ray bursts discussed above. These puzzling systems may be related to non-^{56}Ni producing supernovae or they may be merger gamma-ray bursts with longer durations than usually found (Gehrels et al. 2006; Fynbo et al. 2006; Della Valle et al. 2006; Gal-Yam et al. 2006; Ofek et al. 2007).

(*c*) *Mind the gap*

It is quite remarkable that current observations reveal a clear gap between the brightnesses of gamma-ray burst supernovae, at around absolute magnitude -17 to -19, and the upper limits on long supernova-less gamma-ray bursts at around -12 to -14 mag. Finding faint supernovae is of course difficult and fainter supernovae will likely be detected but the current factor of 100 may indicate that there is not a simple continuum of events.

4. Engine-driven supernovae

The collapsar model (MacFadyen & Woosley 1999) operates with two time scales, the duration of the active 'engine' (jet), t_E, and the time for shock breakout, t_S. A successful gamma-ray burst requires the engine to be active for longer than the shock-breakout time. Bromberg et al. (2011) and Lazzati et al. (2012) have used this picture to explore the consequences of the relative durations for the resulting supernovae and gamma-ray bursts (an alternative jet scenario is presented by Papish & Soker 2011):

- $t_E > t_S$: a normal jet gamma-ray burst accompanied by a Ic-BL is produced
- $t_E \approx t_S$: a low-luminosity gamma-ray burst accompanied by a Ic-BL or a relativistic Ic-BL with no gamma-ray burst is produced
- $t_E < t_S$: a non-relativistic supernova but no gamma-ray burst is produced

In this picture, relativistic supernovae, like SN 2009bb (Soderberg et al. 2010; Pignata et al. 2011) are jet-driven supernovae, similar to low-luminosity gamma-ray bursts. It is worth noting that a low luminosity is not necessarily synomynous with a short engine duration, i.e., it may be possible to have low-luminosity jet gamma-ray bursts, such as possibly GRB 120422A.

In the collapsar model, one could also imagine that the engine does not occur in a stripped-envelope core-supernova but in a Type II supernova with a hydrogen and/or helium layer which would prevent the escape of the jet (see also Heger et al. 2003). Such massive stars may have a dense circumstellar medium which would make them appear as Type IIn supernovae, as suggested by e.g., Nomoto et al. (2003) and Chevalier (2012). Recently a possible jet-powered IIn (SN 2010jp) was reported (Smith et al. 2012), albeit not a relativistic one.

The picture regarding jet-driven supernovae and gamma-ray bursts that emerges from the discussion in this paper is summarised in Table 1. SN 2012bz/GRB 120422A, which may be a transition object between the low-luminosity and jet gamma-ray bursts, reminds us that this fairly simple picture could easily be more complex.

Table 1. The supernova/gamma-ray burst/jet connection

Core-collapse supernovae	Supernova/gamma-ray bursts	Gamma-ray bursts
Relativistic Ic-BL (SN 2009bb)	Low-luminosity GRBs (SN 1998bw/GRB 980425)	Fall-back supernovae? (GRB 060505)
Type IIn? (SN 2010jp)	Jet GRBs (SN 2003dh/GRB 030329)	Mergers (GRB 050509B)

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References

Amati, L., Frontera, F., & Guidorzi, C. 2009, A&A, 508, 173

Amati, L., Guidorzi, C., Frontera, F., Della Valle, M., Finelli, F., Landi, R., & Montanari, E. 2008, MNRAS, 391, 577

Bromberg, O., Nakar, E., & Piran, T. 2011, ApJ, 739, L55

Campana, S., et al. 2006, Nature, 442, 1008

Cano, Z., et al. 2011, ApJ, 740, 41

Chevalier, R. A. 2012, ApJ, 752, L2

Colgate, S. A. 1968, Canadian Journal of Physics, 46, 476

Crowther, P. A. 2007, ARA&A, 45, 177

Della Valle, M., et al. 2006, Nature, 444, 1050

Drout, M. R., et al. 2011, ApJ, 741, 97

Fynbo, J. P. U., et al. 2006, Nature, 444, 1047

Gal-Yam, A., et al. 2006, Nature, 444, 1053

Galama, T. J., et al. 1998, Nature, 395, 670

Gehrels, N., et al. 2006, Nature, 444, 1044

Granot, J., & Ramirez-Ruiz, E. 2010, arXiv:1012.5101

Heger, A., Fryer, C. L., Woosley, S. E., Langer, N., & Hartmann, D. H. 2003, ApJ, 591, 288

Hjorth, J., & Bloom, J. S. 2011, arXiv:1104.2274

Hjorth, J., et al. 2003, Nature, 423, 847

—. 2005a, ApJ, 630, L117

—. 2005b, Nature, 437, 859

—. 2012, ApJ, 756, 187

Kann, D. A., et al. 2010, ApJ, 720, 1513

Kocevski, D., et al. 2010, MNRAS, 404, 963

Kouveliotou, C., Meegan, C. A., Fishman, G. J., Bhat, N. P., Briggs, M. S., Koshut, T. M., Paciesas, W. S., & Pendleton, G. N. 1993, ApJ, 413, L101

Kulkarni, S. R. 2005, arXiv:astro-ph/0510256

Kulkarni, S. R., et al. 1998, Nature, 395, 663

Langer, N. 2012, ARA&A, 50, 107

Lazzati, D., Morsony, B. J., Blackwell, C. H., & Begelman, M. C. 2012, ApJ, 750, 68

Li, L.-X., & Paczyński, B. 1998, ApJ, 507, L59

Lipkin, Y. M., et al. 2004, ApJ, 606, 381

MacFadyen, A. I., & Woosley, S. E. 1999, ApJ, 524, 262

Malesani, D., et al. 2012, GRB Coordinates Network, 13277, 1

Melandri, A., et al. 2012, A&A, 547, A82

Metzger, B. D., et al. 2010, MNRAS, 406, 2650

Nakar, E., & Sari, R. 2012, ApJ, 747, 88

Nomoto, K., Maeda, K., Mazzali, P. A., Umeda, H., Deng, J., & Iwamoto, K. 2003, arXiv:astro-ph/0308136

Ofek, E. O., et al. 2007, ApJ, 662, 1129

Papish, O., & Soker, N. 2011, MNRAS, 416, 1697

Pian, E., et al. 2006, Nature, 442, 1011

Pignata, G., et al. 2011, ApJ, 728, 14

Podsiadlowski, P., Mazzali, P. A., Nomoto, K., Lazzati, D., & Cappellaro, E. 2004, ApJ, 607, L17

Roberts, L. F., Kasen, D., Lee, W. H., & Ramirez-Ruiz, E. 2011, ApJ, 736, L21

Rosswog, S., & Ramirez-Ruiz, E. 2002, MNRAS, 336, L7

Smith, N., & Owocki, S. P. 2006, ApJ, 645, L45

Smith, N., et al. 2012, MNRAS, 420, 1135

Soderberg, A. M., et al. 2006, Nature, 442, 1014

—. 2010, Nature, 463, 513

Sparre, M., et al. 2011, ApJ, 735, L24

Stanek, K. Z., et al. 2003, ApJ, 591, L17

—. 2005, ApJ, 626, L5

Troja, E., et al. 2012, ApJ, 761, 50

Wiersema, K., et al. 2012, GRB Coordinates Network, 13276, 1

Woosley, S. E., & Bloom, J. S. 2006, ARA&A, 44, 507

Zhang, B.-B., et al. 2012, ApJ, 756, 190